

NOISE IN STATE OF THE ART CLOCKS AND THEIR IMPACT FOR FUNDAMENTAL PHYSICS

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Frequency, time, and phase are the most precisely determined of all physical parameters. Because of this, advanced atomic clocks are used to test the domain of validity of the physical laws. Atomic clocks produce signals with the highest achievable frequency stability. The ultra-low noise performance of advanced atomic clocks is due to three important features. First, fundamental processes that determine the inherent noise of the atom are quantum mechanical, and may be used to advantage for the highest performance. Second, atomic species used in clock applications are selected for their inherently low sensitivity to environmental influences. Finally, atoms may be shielded to minimize the deleterious influence of the environment. Despite these features, atomic clocks, as with any physical device, suffer from a variety of noise sources that result in output signals with less than ideal characteristics. They exhibit various features in their noise spectrum, including $1/f$ and colored components, which represent a limitation in their application for testing the fundamental laws. In this paper a review of the use of advanced atomic clocks in testing the fundamental physical laws will be presented. Noise sources of clocks will be discussed, together with an outline their characterization based on current models. The paper will conclude with a discussion of recent attempts to reduce the fundamental, as well as technical noise in atomic clocks.

I. Introduction

The most precisely determined physical parameter is time, or equivalently frequency or phase. Since atomic clocks and frequency standards provide the highest precision time and frequency reference signals, they naturally play a pivotal role in testing physical laws to determine their boundaries of applicability. Because of this, there is continuous effort to improve the performance of clocks and frequency standards to improve the sensitivity of tests and the resolution of measurements. Thus the issue of noise, both fundamental and instrumental, is crucial to the development of ultra-high performance atomic clocks.

In this paper a short review of the role of clocks in tests of fundamental physics is given, and a discussion of the physics of atomic clocks is presented. Based on this, the major sources of fundamental and technical noise are identified. Current strategies to reduce or minimize the influence of noise on the performance of clocks, and frequency standards, is then

discussed, followed by a summary and a short consideration of the future outlook.

Before we begin, two important points must be mentioned. First, throughout this paper clocks and frequency standards are referred to as though they are the same instruments. This of course is not strictly speaking correct. Clocks provide time keeping capability, and thus their performance is determined by their accuracy. Accuracy is a parameter that measures the deviation of the frequency of a clock from the frequency of a specific hyperfine transition in the cesium atom, which is selected to define the unit of time, second. In principle, and in practice, an atomic clock may operate only periodically, when the systematic effects that influence the frequency of operation of the clock are carefully determined, so that the undisturbed frequency of the atomic clock may be obtained, and the elapsed time interval is established.

Frequency standards, on the other hand, are characterized by high stability. Stability refers to the degree to which the frequency of the standard remains constant over a (usually long) period of measurement. Frequency standards do not necessarily have high accuracy, but exhibit high frequency stability. Atomic clocks with high accuracy, and the accuracy of a clock is not higher than its stability. Of course, the inverse of this statement is not true for frequency standards.

Having established this distinction, it is important to point out the nearly all measurements require frequency stability over a period of time corresponding to the phenomenon of interest. Thus tests of the physical law more often than not, require stability, and not accuracy. This statement is not true for all cases, but is true for most of the measurements in space. Finally, clocks are also used in other precision applications such as spacecraft navigation [1], and radio occultation experiments [2] with microwave links between a spacecraft and a ground station. The first of these requires long term stability, and the second requires short term stability. The case of experiments with stabilized radio links to a search for gravitational waves [3] will be briefly considered below.

Because of the scope of this paper, only introductory descriptions are provided here. The interested reader is referred to the references for detailed descriptions.

II. Tests of Fundamental Laws with Atomic Clocks

A major test of physics performed by clocks in space is related to a search for the breakdown of general relativity. An important feature of Einstein's field equation is that it contains no free parameters, and any deviation from its predictions would signal a breakdown of the theory. A particular prediction of the theory of relativity is the gravitational clock shift corresponding to a shift in the frequency of two clocks located at two points with a gravitational potential difference. On the earth's surface, two clocks separated by a height of a meter exhibit a difference in frequency of a part in 10^{16} . This prediction can be tested by comparing the frequency of clocks that are placed, one on the ground and the other in a spacecraft orbiting the earth. Such an experiment, first performed with a hydrogen maser frequency standard on the Gravity Probe A mission [4], is currently the subject of new investigations armed with more stable and accurate clocks. Two such experiments have been recently selected by NASA for flight onboard the International Space Station (ISS). The first, scheduled to fly in 2005, is the Primary Atomic Reference Clock in Space (PARCS) based on a laser-cooled cesium clock [5]. PARCS is expected to significantly improve on the measurement of the clock redshift performed by Gravity Probe A. The second is the Rubidium Atomic Clock Experiment (RACE), based on a laser-cooled rubidium clock [6]. RACE is expected to fly in 2007, and if combined with a third clock experiment based on a superconducting cavity oscillator, will provide a 5000-fold improvement in the test of Local Lorentz Invariance (LLI), one of the elements of Einstein's general theory of relativity. An ensemble of clocks including a hydrogen maser and a laser-cooled cesium clock is planned by the European Space Agency, ESA, for another test of the relativistic prediction for the clock shift. This experiment, ACES, is expected to fly in a time window that might overlap with RACE. If so, there will be a unique opportunity to compare clocks in flight, and to obtain even higher science returns than planned for each individual clock.

SpaceTime is another mission currently under study that aims to test fundamental physical laws with atomic clocks [7]. This mission is based on comparing the frequency derived from three different atoms in the vicinity of the Sun, where more than 95% of the mass in the solar system resides. The strong gravitational field near the sun allows the highest achievable sensitivity to a possible variation of the fine-structure constant, α , which will manifest itself in a difference in the frequency drift rates of the three atomic species. This experiment is based on a special 'tri-clock'

consisting of three ion traps in the same vacuum, thermal, and magnetic-field environment. The traps will hold ions of mercury, ytterbium, and cadmium, each of which is used to realize one of the three clocks. This instrument will fly within four solar radii of the sun, in a spacecraft designed to provide a benign environment despite the intense solar radiation. The journey to the sun will be via a Jupiter flyby, and would take about five years.

Finally, the frequency stability and the spectral purity of the microwave radio links between spacecraft and the ground are exploited extensively to obtain new scientific findings. For example, the microwave link between the ground station and the spacecraft acts as an “antenna” for detecting gravitational waves [3]. This unique antenna system responds to a propagating gravitational wave, which imprints a telltale signature with three short components on the Doppler data residuals received on Earth. Two of these are due to the buffeting of the earth and the spacecraft by the traveling wave; the third is a signal originating from the buffeted earth that is reflected back by the spacecraft transponder. This antenna is particularly useful in the search for very long wavelength gravitational waves (as determined by the earth-spacecraft distance) that are outside the sensitivity range of earthbound antennas such as LIGO.

III. Technical Background and Clock Noise

In this section a general discussion of the physical and operational basis of atomic standards is presented. Atomic standards are superior to man-made composite resonators, e.g., quartz crystal or cavity resonators, since any one atom of a species is indistinguishable from the next, for example, one cesium atom from the other. This feature ensures that atoms as clocks can be more reproducible in their operating frequency than any macroscopic crystal or cavity resonator ever constructed, since no two such resonators will ever be exactly identical.

Atomic frequency standards are based on the simple quantum mechanical relation between the energy difference of two atomic energy levels and the frequency of the photon connecting these levels in an emission or absorption process: $\Delta E = h\nu$. Here ΔE is the energy separation of the two levels, h is Planck's constant and ν is the frequency of the photon. Based on this relation a comparison of the frequency of an external oscillator

with the frequency of a photon connecting two atomic energy levels can lead to a frequency standard.

The actual realization of the clock has several steps: 1) preparation of the atoms in the desired energy state, 2) excitation of the atoms with photons generated by the local oscillator, 3) comparison of the frequency of the local oscillator with that of the atoms, and 4) feedback to correct the frequency of the LO. A number of sources of intrinsic and technical noise related to the above steps influence the performance of the clock. Since atomic energy levels respond to any applied electric and magnetic fields, atoms must be shielded from the environment, and from the deleterious influence of applied fields required to prepare the atom in the desired state. Collisions with the containing vessel, and with other atoms and molecules must also be minimized since they shift the energy levels, as well. Furthermore, any changes in the applied field from the LO due to thermal effects or caused by the local oscillator noise are also noise sources that degrade the clock performance.

In their operation, atomic frequency standards transfer the stability of an atomic resonance to steer a local oscillator (LO), which in the case of microwave standards is usually a 5 MHz quartz crystal oscillator. The local oscillator is characterized with a stable frequency typically over periods of from 1 to 100 seconds, but its frequency drifts or otherwise degrades for longer time spans. Outlining the procedure used to correct such frequency changes in an LO reveals some of the desirable properties of an atom to be used as the basis for an atomic clock. For example, Cesium and Rubidium atoms, and mercury ions are attractive because their large resonance frequency is more sensitive to variations in LO frequency changes. Thus a frequency step in the LO of 5×10^{-13} corresponding to 2.5 μHz at the 5 MHz operating frequency will be multiplied to 20 mHz at the $\nu_0 = 40.5$ GHz mercury resonance but only to 0.7 mHz at the $\nu_0 = 1.4$ GHz hydrogen resonance. With equal frequency discrimination at the atomic resonance the higher operating frequency will clearly steer the LO in a more stable lock. Frequency discrimination at the atomic resonance is determined by the sharpness of the atomic resonance line, $\delta\nu$, together with SNR achieved in the measurement of this line. These three parameters determine the stability of the LO when locked to the atomic resonance; $\text{stability} = \delta\nu/\nu_0/\text{SNR}$. Since SNR increases as square root of the measurement intervals for white noise processes such as the photon or atom counting in detecting the atomic transition, we find that stability is equal to :

$$1/(Q \times SNR \times \sqrt{\tau})$$

where we have introduced the line quality parameter, $Q = \nu_0/\delta\nu$. The improvement in frequency stability gained through averaging over longer time intervals breaks down, however, when inevitable changes in the atomic environment lead to small changes in the atom's resonant frequency. It is of great practical importance, however, that atomic transitions exist which are far more immune to changes in the atomic environment than any man-made oscillator. Nevertheless, isolation from environmental perturbations drives the technology and the development of all atomic frequency standards. The choice of the atom to be used as the clock determines the sensitivity to external perturbations and how much shielding from these environmental changes will be necessary to reach a given level of stability. Because the shielding adds a great deal to the bulkiness and complexity, it is especially important for space borne clocks, where low mass and high reliability are paramount, that the standard be inherently immune to environmental changes so that only relatively modest shielding is required.

The sensitivity of the atomic resonance frequency to temperature variations determines the complexity of the thermal engineering and regulation necessary to shield against thermal perturbations in the environment. This sensitivity is set by the second order Doppler shift of the atoms in thermal motion at temperature T , and the fractional frequency shift which is given by $d\nu/\nu = -3k_B T/(2mc^2)$ where k_B is Boltzmann's constant and mc^2 is the rest mass of the atom. For a fixed temperature change Hg^+ ions show only 0.5% of the corresponding frequency shift of hydrogen atoms. In the case of laser cooled cesium and rubidium standards, the second order Doppler is rendered practically negligible; the atoms are as cold as a few micro-Kelvin due to their interaction with the laser light [8]. Thus thermal regulation would be much less demanding for these standard. For science applications where ultra-high performance is required, careful thermal designs for cesium, for example, would be required to reduce the influence of more subtle effects, such as a shift of the energy levels due to interaction with the environmental Black Body radiation.

Another large source of perturbation to the atomic resonance frequency is the variations in the ambient magnetic field. The atomic physics of the

magnetic interaction within the ground state hyperfine levels used for the clock transition shows that the fractional frequency sensitivity to a magnetic field change experienced by the atom is proportional to H_0/ν_0^2 , where H_0 is the strength of the applied magnetic field at the location of the atom, and ν_0 is the frequency of the atomic transition used for clock operation. For example, since mercury has a 40.5 GHz atomic splitting it will be 20 times less sensitive than cesium, 35 times less than rubidium, and 840 times less than hydrogen for the same operating field H_0 . Atoms with large clock splitting require less magnetic shielding to reach the same insensitivity to ambient field variations.

The stability obtained with atomic frequency standards is a result of success with which the above steps are implemented. Different approaches have produced different instruments, the most notable of which are the rubidium standard, the cesium beam standard and the trapped ion standard. In the case of the laser cooled cesium and rubidium clocks their long term stability, reproducibility, and accuracy make them the instrument of choice for time keeping and for applications where very long term stability is required.

Aside from the technical noise, atomic clocks are also limited by fundamental quantum mechanical noise. These include the shot noise associated with the finite number of photons and atoms, and the quantum projection noise associated with the system of two energy levels involved in the clock transition. The Heisenberg uncertainty principle is typically not a limitation, since the natural width of the transition (or equivalently the inverse of the lifetime of the transition) is extremely small, and the linewidth of the clock transition is only determined by the interaction time of atoms with the applied radiation supplied with the LO. Strategies to circumvent the fundamental quantum limit achievable with clocks have been proposed.

Finally, it should be mentioned that the performance of clocks can, in principle, be improved if atomic optical transitions, rather than microwave transitions discussed above, are employed. This is because the inherent stability of the clock related to the $Q = \nu_0/\delta\nu$ improves with the frequency of the optical transitions, ν_0 , which is in the 10^{14} range. Furthermore, it is possible to realize optical clocks based on a single laser cooled ion. Such a system can be extremely effectively shielded from the environment, resulting in improved performance. Clocks of this type have been under

development for some time,[9] but only recently have become practical.[10] This is mainly due to a previous lack of a practical technique to divide the optical frequency to a range useful for electronic applications. Advances in the development of simple and practical frequency division from the optical to the microwave range [11] have made this realization possible.

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